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Free-Piston Stirling Technology for Space Power

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FREE-PISTON STIRLING TECHNOLOGY FOR SPACE POWER

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ABSTRACT

An overview is presented of the NASA Lewis Research Center free-piston Stirling engine activities directed toward space power. This work is being carried out under NASA's new Civil Space Technology Initiative (CSTI). The overall goal of CSTI's High Capacity Power element is to develop the technology base needed to meet the long duration, high capacity power requirements for future NASA space missions. The Stirling cycle offers an attractive power conversion concept for space power needs.

Discussed in this paper is the completion of the Space Power Demonstrator Engine (SPDE) testing - culminating in the generation of 25 kW of engine power from a dynamically-balanced opposed-piston Stirling engine at a temperature ratio of 2.0. Engine efficiency was approximately 22 percent. The SPDE recently has been divided into two separate single-cylinder engines, called Space Power Research Engines (SPRE), that now serve as test beds for the evaluation of key technology disciplines. These disciplines include hydrodynamic gas bearings, high-efficiency linear alternators, space qualified heat pipe heat exchangers, oscillating flow code validation, and engine loss understanding. The success of the SPDE at 650 K has resulted in a more ambitious Stirling endeavor - the design, fabrication, test and evaluation of a designed-for-space 25 kW per cylinder Stirling Space Engine (SSE). The SSE will operate at a hot metal temperature of 1050 K using superalloy materials. This design is a low temperature confirmation of the 1300 K design. It is the 1300 K free-piston Stirling power conversion system that is the ultimate goal;

to be used in conjunction with the SP-100 reactor. The approach to this goal is in three temperature steps. However, this paper concentrates on the first two phases of this program - the 650 K SPDE and the 1050 K SSE.

INTRODUCTION

NASA Lewis started work on free-piston Stirling engines around 1977. Today, approximately 20 professionals are engaged in free-piston Stirling technology at NASA Lewis. These free-piston projects include (a) NASA's new Civil Space Technology Initiative (CSTI), which will comprise the major emphasis of this paper, (b) a NASA Lewis project, identified as the Advanced Stirling Conversion Systems (ASCS), to develop Stirling engine technology for terrestrial solar energy conversion that is supported by an interagency agreement with the Department of Energy (DOE) and Sandia National Laboratory (SNL), and (c) a NASA Lewis Stirling Power Generating System (SPGS) project that is supported by an interagency agreement with DOE and Oak Ridge National Laboratory (ORNL). The ASCS project is based upon the use of current technology to demonstrate a system on-sun that is capable of generating 25 kW of electricity within DOE's long-term cost constraints (Ref. 1). The SPGS project is based upon the synergistic characteristics between space power and residential/commercial heat pumps. These characteristics include high efficiency, low vibration, potential for long life and high reliability, and independence of heat source or fuel.

Due to a length constraint, the discussion contained in this paper will be limited to NASA's High Capacity Power element whose overall goal is to develop the technology base needed to meet the long duration, high capacity power requirements for future NASA space missions.

NEED FOR SPACE POWER

NASA's space power technology history has concentrated on systems delivering less than 10 kW, as shown in Fig. 1. The exception was Skylab,

which was designed to deliver nearly 20 kW to the user. Power requirements of NASA's missions, in the past, have been met almost exclusively by photovoltaic (PV) and electrochemical storage systems. Over the next several decades, the amount of electric power in space is expected to grow immensely. Tomorrow's space platforms will continuously require hundreds of kilowatts; and some will periodically consume many megawatt-hours. These space platforms will include manned space stations, communication stations, surveillance platforms, and defensive weapons. These large power systems will be quite different from today's solar arrays.

These projections of space power growth tend to show broad trends as shown in Fig. 1. These broad trends are a direct result of uncertainties in future mission capabilities and needs. It is, however, clear that future space power needs may be several orders of magnitude greater than anything that has been accomplished to date. The challenge for the space planner is formidable - to select power technologies that can meet the projected trends and adapt to multiple users. NASA Lewis, as the primary NASA center for space power research and technology, has contributed significantly to these technologies. Only recently, we have expanded our research into technologies which offer promise of hundreds to thousands of kilowatts of electrical power in space.

These expanded research areas cover a broad base of advanced technology. The first step toward this research and technology advancement is through CSTI. This 5-year technology program is the precursor to NASA's bold new missions. The resulting technology will enable and greatly enhance NASA missions while restoring the Agency's technical capability. The CSTI program not only focuses on space power but also on transportation systems, operations and science. CSTI started in 1988 and will end in 1992 and at that time should have generated critical data from which the Agency can make decisions

on new initiatives. One space power system candidate for these bold missions is the free-piston Stirling engine.

The free-piston Stirling is a rapidly emerging technology which has only recently attracted considerable attention because of the successful Space Power Demonstrator Engine (SPDE). A recent scaling study indicates that it may be possible to build a free-piston Stirling engine/linear alternator system with up to 500 kWe per cylinder capability. Less than 5 years ago it was considered a major achievement to build and successfully operate a 3 kWe free-piston Stirling engine.

ADVANCED STIRLING TECHNOLOGY

The Advanced Stirling Technology project is a significant segment of the NASA CSTI High Capacity Power element. The objective of the project is to demonstrate the capability needed to proceed toward development of space qualified free-piston Stirling engine technology to meet future mission needs. At this point, a fair question is, "Why free-piston Stirling for space power?" The Stirling free-piston system has many attractive attributes, several of which are tabulated in Fig. 2. Specifically, the Stirling cycle has the highest efficiency for the same given heat input and heat rejection temperatures. Because the Stirling system employs the gas bearing - either hydrodynamic or hydrostatic - there is the potential for long life and high reliability.

A Stirling engine/linear alternator system has only two moving parts per cylinder - that is the displacer and the power piston/alternator plunger. The result is a relatively simple configuration. An opposed-piston engine with reciprocating components along the same axis - such as the Space Power Demonstrator Engine which will be discussed later in this report - is an inherently balanced power module. A single-cylinder engine can be balanced either actively or passively using a spring-mass combination. A passive

system is good for only a narrow frequency range; and an active system which has a variable spring rate, provides a wide range over which the vibration can be significantly reduced.

Free-piston Stirling engines contain no sliding rod seals such as those present in the kinematic concepts. The energy conserved by not having to overcome the losses in the frictional rod seals is not totally without cost. Unlike the kinematic, the free-piston Stirling concept utilizes gas springs which have hysteresis losses. At the present time, it is not known whether the free-piston concept or the kinematic concept is the most efficient, but it is felt that there should not be much difference between the efficiencies of the two concepts. The fact that there is no oil inside the engine makes the free-piston a strong candidate for long life. There is no chance of getting oil contamination into the regenerator and degrading engine performance. An opposed-piston free-piston Stirling engine with a common expansion space has the potential for graceful degradation in the event that one-half of the engine has larger losses than the other. Both pistons would continue to produce power, but at a reduced level.

SP-100 systems studies have been conducted that show the growth potential of Stirling-space-power conversion systems when operated at peak temperatures of 1300 K. As a result, engine hardware demonstrations are planned at three temperature levels: 650, 1050, and 1300 K. The 650 K engine was the Space Power Demonstration Engine (SPDE), the results of which are presented in Refs. 2 to 6. The success of the SPDE engine was the basis for a Stirling power conversion system to be designed to meet space power requirements. The design will ultimately be for a 1300 K application using refractory metals and/or ceramic components. However, because of the expense associated with an engine of this technology advancement (1300 K temperature, nonconventional materials, and a unique test environment), a lower temperature concept was

chosen for the first space test engine. This concept uses 1050 K as the peak temperature, thereby enabling superalloy materials - rather than refractory materials - to be used. This engine is called the Stirling Space Engine (SSE). Figure 3 is a flow diagram showing the evolution of a 1300 K Stirling Space Engine (SSE) from the 650 K SPDE. This figure will be used later in explaining the component development work. It is anticipated that except for materials and modest changes, the two designs (1300 and 1050 K) will be similar.

COMPLETION OF SPDE TESTING

In October of 1986 the SPDE developed 25 kW of engine power. After this successful demonstration - even though the linear alternator supplied only 17 kW of electrical power - the engine was cut in half. One half is undergoing testing at NASA Lewis and the other half at the contractor's site, Mechanical Technology Inc. (MTI) in Latham, New York. These engines are now called Space Power Research Engines (SPRE) and serve as test beds for evaluation of key technology areas such as linear alternators, power-piston hydrodynamic gas-bearings and heat-pipe heat exchangers as pictorially shown in Fig. 4. Figure 5 shows one of these SPRE research engines in a NASA Lewis test cell. The mass attached to the engine at the right in the figure is a ballast mass that absorbs any engine unbalance. The original opposed-piston SPDE is inherently balanced and does not require the mass. For a single-cylinder engine, depending upon whether an active or passive balancing system is employed, the mass penalty may range between 3 to 10 percent. Sunpower Inc., of Athens, Ohio, successfully designed, built, and tested a passive balancing unit for a 1 kW free-piston Stirling at NASA Lewis. MTI has also demonstrated a passive balancer for a 3 kW free-piston Stirling engine. One of the first tests to be conducted at NASA is to determine the amount of

power consumed in a balancing device for a single-cylinder engine which replaces the large ballast mass.

The logic behind testing two SPRE engines is to increase research productivity - not to duplicate testing. The only duplication was performance verification of each SPRE engine. Figure 6 shows some of the MTI acceptance test results. Similar results were obtained at NASA. Engine power is shown as a function of piston amplitude. The total power piston stroke is twice the piston amplitude. Over the range of engine power, efficiency increased from about 20.5 percent at 5 kW to around 22.5 percent at 13 kW. A characteristic of this free-piston Stirling is the engine efficiency insensitivity to significant changes in engine power. Most heat engines do not exhibit this characteristic. It is comforting to know that for power or load changes you are not significantly penalized by efficiency changes.

In August of 1988 MTI was awarded a multi-year \$15.4 million competitive contract to include the design, fabrication and testing of a 1050 K SSE. The 1300 K engine (high temperature Stirling Space Engine, HTSSE) - connected with the dotted line in Fig. 3 - is not a part of the initial procurement. However, Fig. 3 outlines the logic used to proceed from a 650 K engine to a 1300 K engine. The NASA SPRE engine is primarily used to improve engine performance by identifying loss mechanisms and applying corrective action. Some of the losses are identified by means of conducting code sensitivity runs. Codes are upgraded and validated as a result of engine modifications and test data. In addition the NASA SPRE will be used to assess dynamic balancing for a single-cylinder engine. Research results leading to a better understanding of the engine losses will enhance future engine designs.

MTI is working on component development with the other SPRE. Linear alternator efficiency has been upgraded from around 70 percent to about 85 percent. The 85 percent has been demonstrated on a dynamic reciprocating

rig. The improvement has primarily resulted from a materials substitution (nonmagnetic for magnetic materials) thereby reducing the eddy current losses described in Ref. 6. Nonmagnetic materials will be incorporated in the SPRE engine.

A hydrodynamic gas bearing has been successfully demonstrated on the power piston of the SPRE over the range of operating conditions. What makes the concept challenging is the lack of experimental data whereby a rotating hydrodynamic bearing-supported piston is simultaneously required to reciprocate axially while, under the influence of a varying pressure gradient across the bearing length. Reciprocation is about 20 mm total at about 100 Hz frequency. The hydrodynamic bearing - based on early test data - appears to be stable on the power piston due to the side pull of the piston-plunger magnets. There are no such stabilizing magnets on the displacer and the preferred method of developing a gas bearing on the displacer - whether it be hydrodynamic or hydrostatic - is not known at this time.

MTI is also conducting tests on various regenerator configurations in the SPRE engine. These tests will experimentally evaluate the impact on engine power and efficiency and be used in conjunction with code predictions. The next sequence for the MTI SPRE - as shown in Fig. 3 is upgrading the cold end of the engine. The primary purpose of this upgrade is to verify the mechanical integrity and operation of the cold end of the 1050 K SSE engine by operating the cold end at 525 K. A second objective is to determine whether the magnets degrade at this temperature level and affect alternator efficiency.

The next step is to replace the 650 K shell-and-tube hot end of the SPRE with a heat-pipe heater capable of 1050 K operation. After this upgrade the SPRE will have evolved into a 12.5 kWe Component Test Engine (CTE). When this configuration develops the desired power and efficiency, it only need be scaled up by a factor of two to become a single-cylinder SSE. During the MTI

upgrading of SPRE, NASA will provide whatever technology enhancements - be they in code development or component development - that have been developed during the course of SPRE upgrading. Depending upon the progress in fabricating and joining some of the superalloys, the CTE engine may be fabricated from more conventional superalloys thereby sacrificing life to 10 000 hr capability. However, the 25 kWe SSE will be designed for 60 000 hr life with high strength superalloys.

SUPPORTING RESEARCH AND TECHNOLOGY

As part of the CSTI High Capacity Power element, NASA is conducting advanced Stirling technology - some of which is being done in-house. One area under consideration is the Stirling hot-end heat exchanger. Whether the heat source is solar or nuclear, there is a strong probability that heat pipes will be required to transport heat to the engine heat exchangers. Currently there is a paucity of test data relative to liquid-metal heat-transport systems coupled to Stirling engines. An inexpensive 1 kW engine was designed using many existing components from a previously tested engine. This engine incorporated three modular heat exchangers with integral sodium heat pipes. Calculations showed that each of the modules on this small engine would operate at the same conditions as a similar type heat-pipe module on the SSE. To date the heat pipes have operated up to about 975 K with temperature variations of less than 10 K and no known heat pipe problems have occurred. All results indicate that the heat-pipe modules are viable candidates for Stirling cycle heat exchangers. Each heat-pipe module was designed to produce up to 2 kW of power. Details of the heat-pipe modules are given in Ref. 7. The 1 kW heat-pipe Stirling is shown in Fig. 7.

SSE ENGINE

The Stirling Space Engine is an engine design based upon eventual 1300 K operation, but one that will be fabricated initially from superalloy materials

and run at 1050 K to confirm design features. Sunpower provided the initial SSE conceptual design. Currently MTI is conducting the preliminary engine design as part of the NASA-awarded, \$15.4 million, 4-year contract. This 1050 K engine (see Table I for goals and specifications) will serve as a transition from demonstrated Stirling technology feasibility at 650 K peak temperature to 1050 K. The transition will incorporate advanced heat exchangers using sodium heat pipes. Hydrodynamic gas bearings will be used for the piston. The gas bearing method for the displacer has not been determined. An improved alternator design will be used to reduce the losses encountered during SPDE testing. The success of the 1050 K engine may play an important role in various space-power programs. For example, a successful Stirling at 1050 K may necessitate that Stirling be given a closer look for future Space Station missions. Also, depending upon the SP-100 reactor and thermoelectric converter progress, Stirling may deserve another look as a near-term option as well as a growth consideration. However, the main thrust of this work is the technology development of a 1300 K Stirling engine. The 650 and 1050 K engines are only stepping stones toward that objective.

How much progress has been made toward enhancing the technology development of free-piston Stirling engines (FPSE) for space-power application? A partial answer to this question can be obtained by referring to Fig. 8. Back in 1983 the 875 K RE-1000 FPSE developed 1.5 kW/piston at a specific mass to power ratio of 280 kg/kWe. In 1986, the 650 K SPDE produced 12.5 kW/piston at a specific mass to power ratio of 12 kg/kWe; an improvement of more than 20 in specific mass. And, the newly planned 1050 K SSE will develop 25 kW/piston at a specific mass of 6 kg/kWe. This improvement is shown in Fig. 8 - both graphically and pictorially.

LOSS UNDERSTANDING

In general, the accuracy of Stirling engine computer codes in predicting the thermodynamic performance of engines has left a lot to be desired - particularly codes which have not been calibrated. Existing design codes are good enough to design engines that work. However, in order to get the engines to perform well, expensive hardware modifications are usually needed. One of the main reasons for this problem is the lack of proper characterization of thermodynamic losses that occur inside the engine. There is even much disagreement as to which losses are the major losses. In order to resolve this lack of understanding and to generate more accurate design and performance codes, a Stirling engine loss understanding effort has been started by NASA Lewis to address characterization of engine thermodynamic losses. There are both contracts and grants in place investigating loss mechanism areas. Areas that have been identified as requiring better characterization are (a) instantaneous heat transfer rates in the heat exchangers, (b) adiabatic losses - which are described as losses due to mixing of gases at different temperatures and losses which occur when a nearly adiabatic volume is adjacent to a surface in which significant heat transfer occurs, (c) flow maldistributions - deviations from one dimensional flow resulting from poor manifolding, (d) instantaneous heat transfer rates in gas springs and compression and expansion spaces (this heat transfer causes a hysteresis power loss), (e) appendix gap losses, (f) net energy flux per cycle through the regenerator - from heater to cooler, (g) area transition heat transfer and pressure drop, and (h) instantaneous pressure drop across the displacer, and viscous dissipation. Contractual loss understanding efforts are being performed at MTI, Sunpower, the University of Minnesota (two grants), Case Western Reserve University in Cleveland, Ohio, and Gedeon

Associates of Athens, Ohio. A more thorough treatment of the above mentioned loss understanding mechanisms is given in Ref. 8.

CONCLUDING REMARKS

Although Stirling technology is an emerging technology, there is considerable justified interest as to its potential candidacy for space-power missions whether in the tens of kilowatt range or the multimegawatt range. In less than 5 years, under limited funding, the free-piston Stirling accomplishments have been significant. An opposed-piston engine has generated 25 kW of engine power while the engine efficiency was greater than 22 percent at a temperature ratio of 2.0. Engine vibration is exceedingly low. The integrated concept uses a linear alternator and provides a compact power conversion system. Gas bearings were successfully demonstrated on an engine power piston at design conditions. Results of a scaling study show that single-cylinder engines are feasible at power levels as high as 500 kW.

There appears to be no technological break through needed - only verification of system reliability and life and the timely solution of engineering problems in the areas of high efficiency linear alternators; gas bearings for the reciprocating components; heat-pipe heater heads for either nuclear or solar powered systems; and validation of design and performance codes over the complete range of desired power.

A 1050 K engine design is underway and the design - with the exception of materials substitution - should be applicable for 1300 K application. The 1050 K engine should be subjected to an endurance test which will go a long way toward establishing credibility for Stirling space power. The codes for design and performance predictions are constantly being upgraded through fundamental understanding of engine losses.

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TABLE I. - 1050 K STIRLING SPACE ENGINE
GOALS AND SPECIFICATIONS

End of life power, kWe	25
Efficiency, percent	>25
Life, hr	60 000
Hot side interface	Heat pipe
Heater temperature, K	1050
Cooler temperature, K	525
Vibration - casing peak-peak, mm	<0.04
Bearings	Gas
Specific mass, kg/kWe	6.0
Frequency, Hz	70
Pressure, MPa	15.0

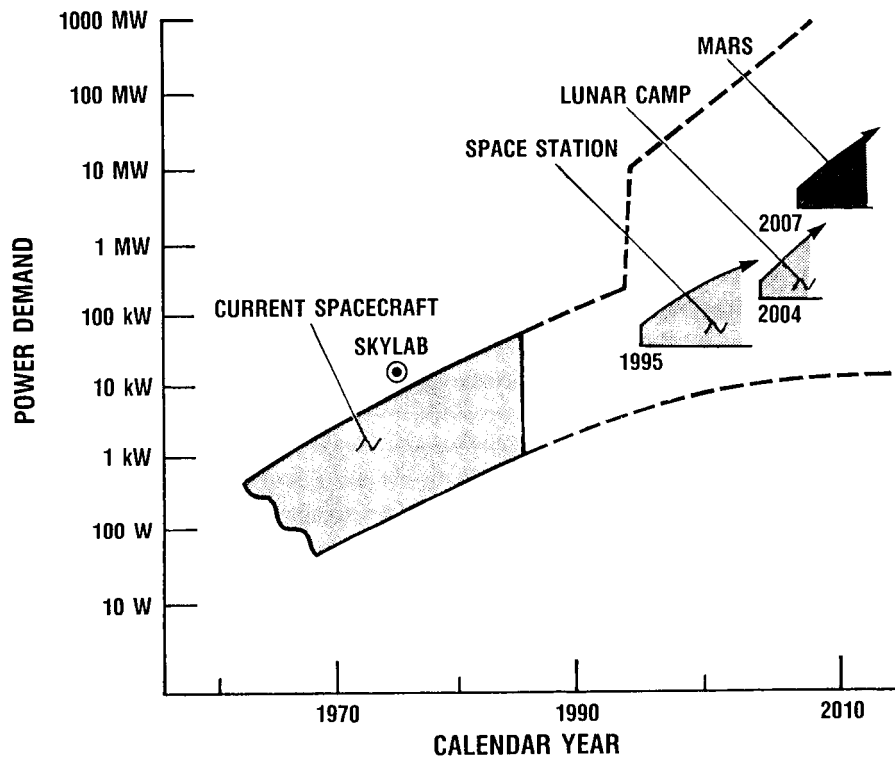


FIGURE 1. - PROJECTED GROWTH IN SPACE POWER.

- HIGH EFFICIENCY (RELATIVE TO OTHER SYSTEMS)
- POTENTIAL FOR LONG LIFE AND HIGH RELIABILITY
- NON-CONTACTING GAS BEARINGS
- TWO MOVING PARTS
- DYNAMICALLY BALANCED
- NO ROD SEALS
- NO OIL INSIDE ENGINE
- POTENTIAL FOR GRACEFUL DEGRADATION
- POWER OUTPUT FLEXIBILITY

FIGURE 2. - WHY FREE-PISTON STIRLING?

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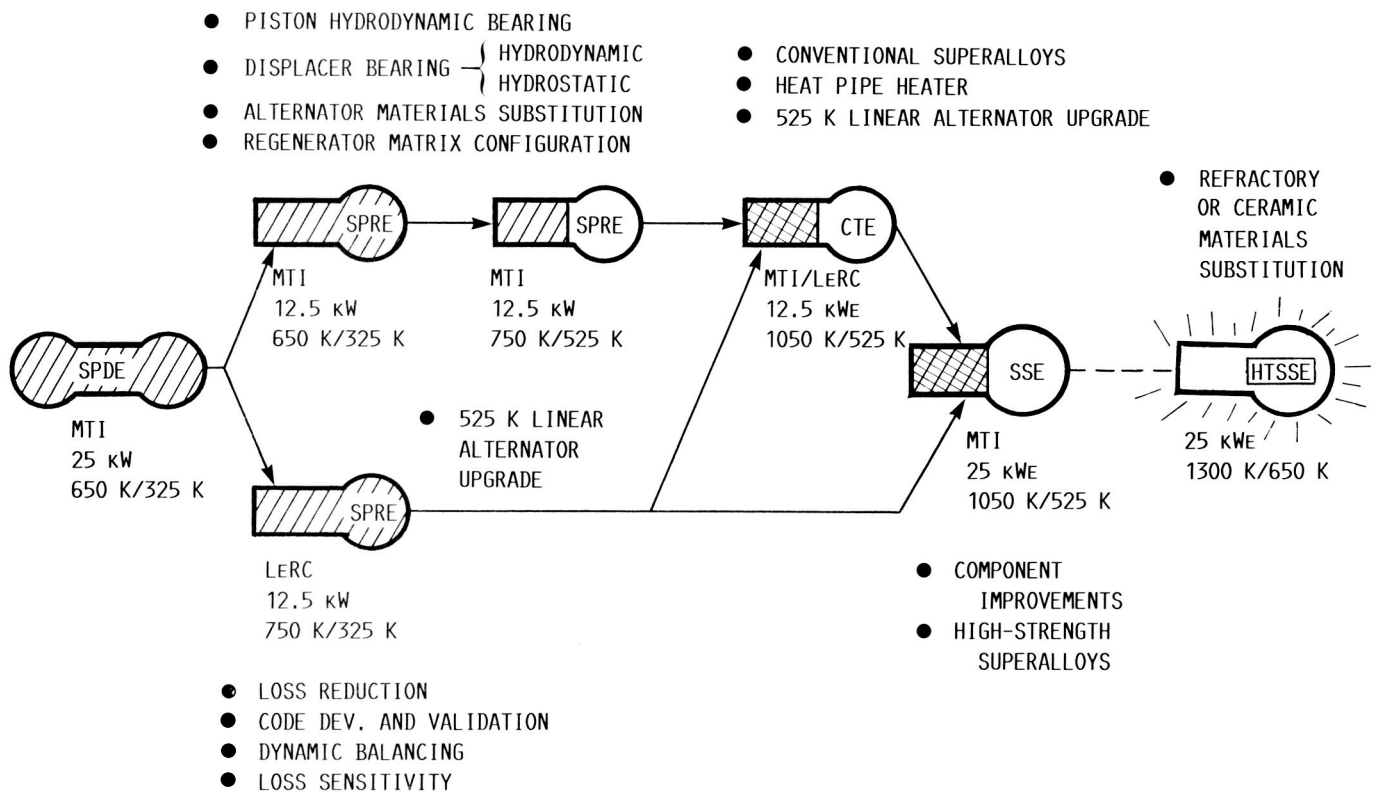


FIGURE 3. - EVOLUTION OF A HIGH TEMPERATURE (1300 K) STIRLING SPACE ENGINE.

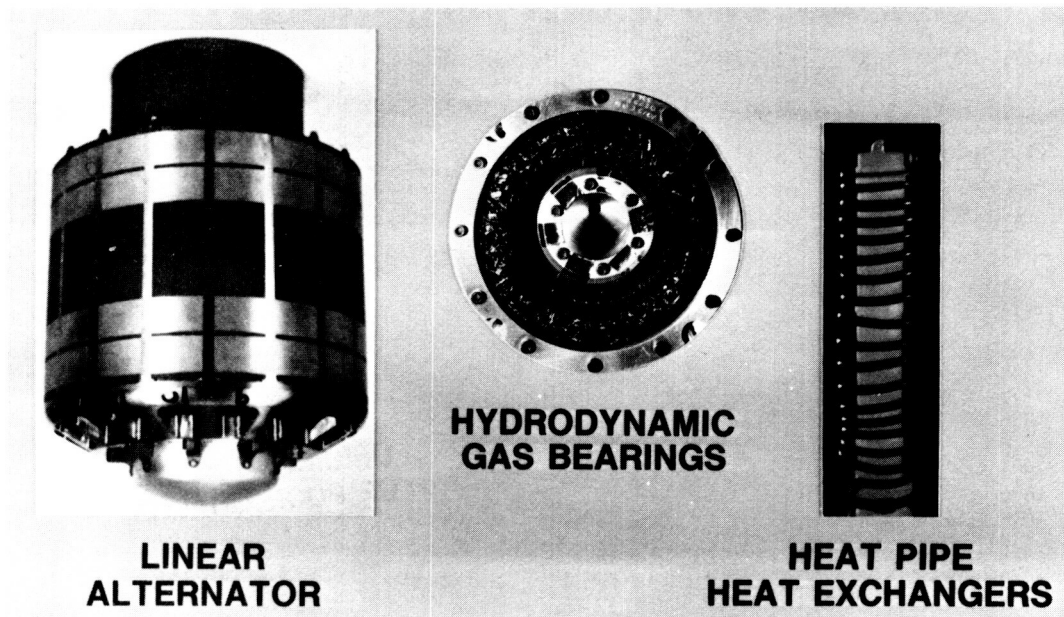


FIGURE 4. - KEY TECHNOLOGY ISSUES.

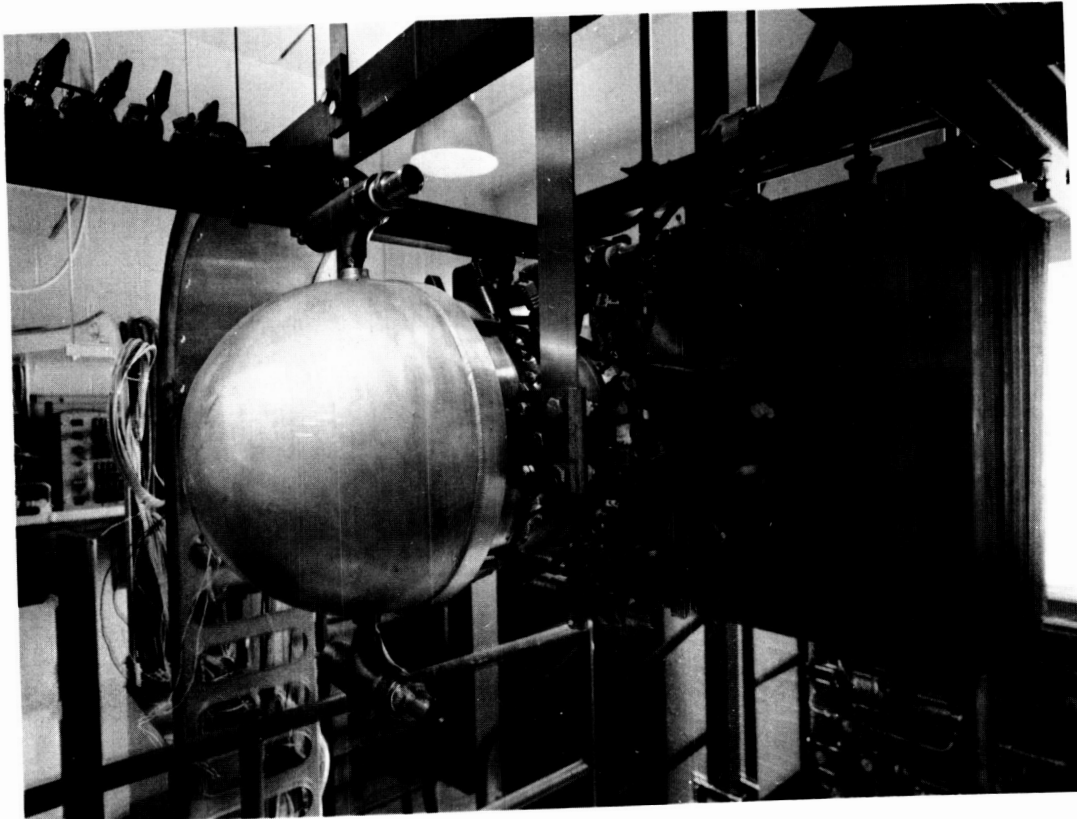


FIGURE 5. - SPACE POWER RESEARCH ENGINE UNDER TEST AT NASA-LERC.

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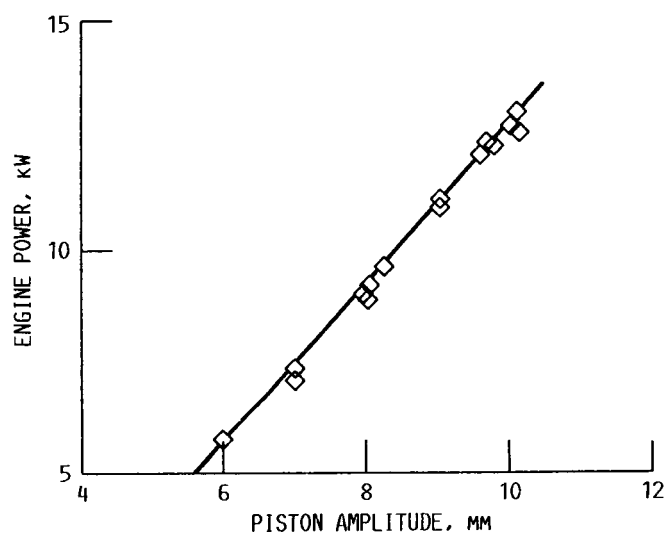
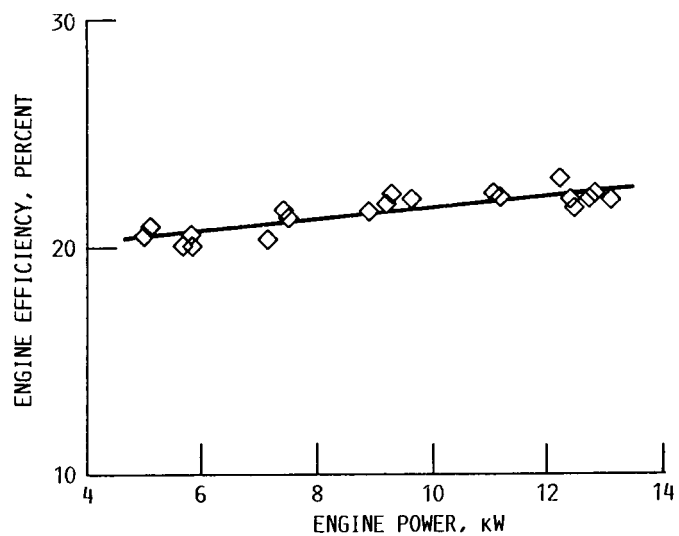


FIGURE 6. - SPACE POWER RESEARCH ENGINE PERFORMANCE AT 150 BAR AND TEMPERATURE RATIO OF 2.0. 5/21/87 TEST DATA.

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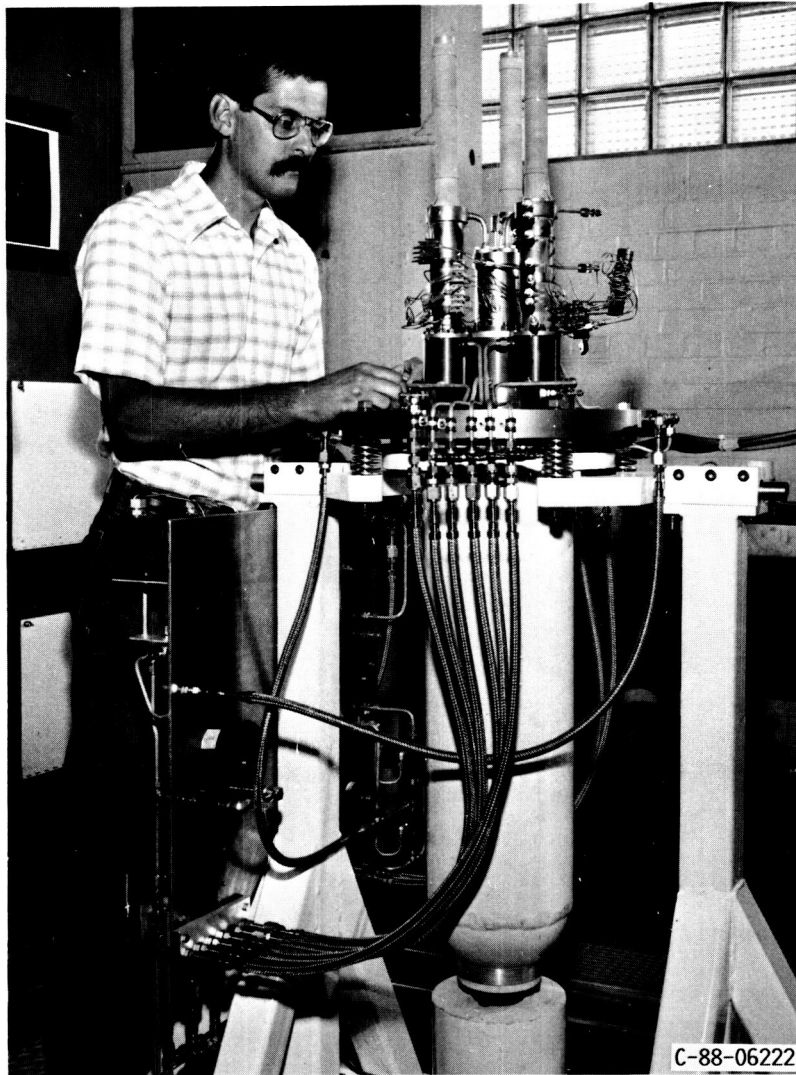


FIGURE 7. - ONE kW FREE-PISTON STIRLING ENGINE POWERED BY THREE
SODIUM HEAT-PIPE MODULES.

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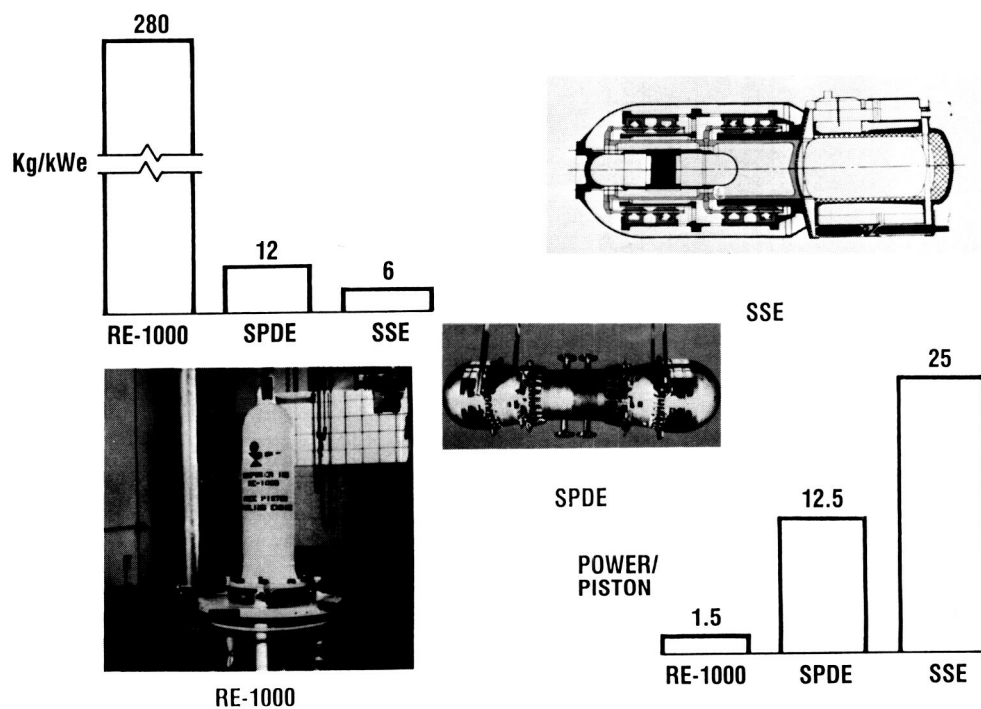


FIGURE 8. - PROGRESS IN FPSE DEVELOPMENT.

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